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ELECTRONIC FREQUENCY REGULATOR

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/Figures referred to are appended./

This article describes an electronic frequency regulator which uses a tuning fork as a standard. The regulator is utilized for the frequency stabilization of a 400-cps generator that supplies power to the network analyzers of the Power Engineering Institute, Academy of Sciences USSR (1). The frequency is stabilized with a regulation accuracy within 0.1%.

The frequency stabilization of alternating current sources at normal power-line frequencies and higher has lately acquired great importance, especially in connection with the development of ac measuring apparatus requiring great frequency stability. In particular, the construction in the Laboratory of Electrical Systems of the Power Engineering Institute, Academy of Sciences USSR, of an ac network analyzer intended for the analysis of complicated electrical circuits and equivalent networks of electromechanical systems (1) required frequency stabilization of its power source (400 cps) with an accuracy exceeding 0.1%.

To meet this requirement, the electronic regulator described below was developed, since existing types of frequency regulators were not satisfactory in the matter of simplicity, reliability, and stability of adjustment to a rigidly fixed frequency.

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1. A frequency regulator should contain a measuring element to determine the deviation of frequency from the norm (standard) and also a frequency-sensitive device to control the motor which drives the generator.

There are two methods of introducing the standard into the measuring element of the regulator. The first method is suggested by the comparison of synchronous (electrical) time with astronomical time, which, essentially, is a method of regulating the integral frequency. The principle of comparison of electrical time with astronomical times makes it possible to obtain a very exact value for the average frequency over a sufficiently long period of time. However, the instantaneous value of frequency can differ greatly from the average frequency during the period in question.

The second method entails a comparison of the instantaneous value of the frequency of a regulated source (generator) with a standard frequency. However, an accumulation of errors in the angle of deviation from a precise time axis can result during each regulating process.

It is essential to maintain the instantaneous value of frequency for a network analyzer within the closest possible limits. Because of this, the second method was chosen. For the network analyzer, as well as for most industrial applications, it is not absolutely essential to have in-phase relationship with any external oscillations. This requirement of in-phase relationship would cause unnecessary complications in regulators, arising chiefly from the necessity of synchronization in starting and the possibility of falling out of synchronization.

The basic element in an instantaneous-frequency regulator which determines the accuracy of stabilization is the standard against which the stabilized frequency is compared.

In electrical regulators, systems in which circuit impedance or phase angle of the reactive elements depends on frequency (i.e., bridges and resonant electrical LC circuits) are employed as standards. These standards have the basic disadvantages that their parameters, which depend on frequency (i.e., capacitance and, even more so, inductance), change in the course of time; furthermore, their values are influenced by various external conditions. This prevents obtaining sufficient accuracy in stabilization and necessitates a frequent checking with external frequency standards and corresponding adjustments.

Piezoelectric quartz crystals and magnetostrictive resonant systems are incomparably better with respect to frequency stability and accuracy. At present, crystal-controlled standards have a high degree of accuracy, but their employment in the regulation of line and higher frequencies is not justified because the regulators would be too complicated. Although regulators with a magnetostrictive system can also give great accuracy, they, too, are comparatively complicated. For this reason, these two types of regulators were not widely adopted for regulation purposes.

In developing regulator systems, particular attention was given to the selection of a frequency standard. Examination of various types of frequency standards finally revealed that best results could be achieved with tuning forks. Not only are they simple and reliable, but they can be easily adjusted with a high degree of accuracy for the necessary frequency; furthermore, tuning forks do not need readjustments for long periods of time. Their most valuable quality is that frequency is nearly independent of external conditions, although fluctations in ambient temperature may cause a change in natural frequency. This influence of temperature, however, is comparatively small and can be considerably reduced by the use of suitable materials. A tuning fork made of ordinary low-carbon steel has a temperature coefficient of $1 \cdot 10^{-4}$, which corresponds to a variation in its natural frequency of 0.01% per $^{\circ}$ C. The employment of special alloys with low temperature coefficients, such as Elinvar or Invar, makes it possible to reduce this rate to 0.001% or less. It is easy to obtain a very high degree of stability in a tuning fork by using a thermostat with it.

2. In the frequency regulator described above, use is made of the property of a tuning fork (inherent in any vibrating system) to try to follow the frequency of externally-applied forced vibrations, with a phase relationship which depends on the difference between the frequency of the external force and the natural frequency of the tuning fork. Thus, if frequency f of the external force is higher than natural frequency f_o of the tuning fork, there will be a phase lag in the vibration.

On the other hand, if frequency f of the external force is lower than natural frequency f_o of the tuning fork, there will be a phase lead. Thus, deviations in frequency f from resonant frequency f_o are transformed into deviations in phase. The dependence of the amplitude and phase of the forced vibrations of a tuning fork on the frequency of the external driving force is indicated in Figure 1. The diagram of the frequency-regulator system is given in Figure 2.

The tuning fork is provided with two coils, L_1 and L_2, and a suitable magnetic system. One of the coils, L_1, is fed by current from the bus bars of the stabilized generator, causing forced vibrations in the tuning fork with a frequency equal to that of the supply current. In the second coil, L_2, the vibrations of the tuning fork develop an alternating electromotive force in phase with the tuning fork vibration. The variation in phase of this electromotive force corresponds in magnitude and sign to the deviation of frequency f from resonance frequency f_o, and therefore it can be utilized (directly or after suitable amplification) in some sort of phase control with ordinary electronic or ionic rectifiers that supply power to the controlling mechanism of the regulator.

In the given case, any scheme can be utilized for transforming variations in phase into corresponding variations in dc voltage, which is most suitable for frequency regulation. After examining a great many practical possibilities, we selected a phase discriminator with two diodes and a control tube, 2, 3. The device adoped consists of control tube V_1 (Figure 2) on the grid of which is applied, in addition to a fixed bias, the voltage from secondary coil L_2 of the tuning fork through shielding transformer T1. Tube V_1 controls the instantaneous value of the total current in twin rectifier V_2 /twin diode 30Ts6 with separate cathodes/, which is fed through transformer T2 from the same bus bars of the stabilized generator. Two identical resistors, R_1 and R_2, connected separately in the two halves of rectifier V_2, serve as the load. The output voltage of the system is taken from points a and b.

The principle of operation of the system is as follows: For 90° phase displacement between the voltage on the grid of tube V_1 and the voltage of the secondary coil of transformer T2, the average current flowing in both arms through resistors R_1 and R_2 are equal and the direct voltage component between points a and b equals zero. With a deviation in phase of the grid voltage of control tube V_1 to one side or the other from the 90° position, the average current in one arm increases with a corresponding decrease in the other arm, and hence a dc voltage component will appear between points a and b, corresponding in magnitude and sign to the phase difference. The ac component between points a and b is removed by condenser C.

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Because of the presence of certain additional parasitic phase shifts originating in transformers T1 and T2 and also in coil windings L_1 and L_2 of the tuning fork, it is necessary to introduce a phase correction in the supply circuit of excited coil L_1. This correction is made by adding inductance L_3 and resistor R_3 of such a value that for $f = f_0$ the voltage phase on the grid of tube V_1 will be shifted exactly 90° relative to the voltage of the secondary winding of transformer T2. A 6L6 beam power tube is used as control tube V_1. The supply voltage and screen grid bias for tube V_1 are provided by an auxiliary rectifier with tube V_5 (5Ts4).

To illustrate the relationships of these quantities, Figure 3 shows one of the curves of output voltage as a function of phase shift of the input voltage, obtained experimentally. The curve is plotted for arbitrary deviations in phase of an input voltage of constant amplitude of 10 v (effective) and for an output load (between points a and b) equal to 2,500 ohms.

Figure 4 shows the dependence of output voltage of the converter circuit, together with the tuning fork, on the supply frequency for three maximum values (corresponding to $f = f_0$) of voltage in the secondary winding of the tuning fork: V_g max = 10, 20, and 40 v, and for the same load at the output. As may be seen in Figure 4, the output voltage is linearly dependent on frequency, in changing from minimum to maximum, in limits of ± 0.25 cps, i.e., ± 0.06%. This range of frequency deviation in which the regulator normally operates is determined by the amount of attenuation of the tuning fork. By increasing or decreasing the attenuation of the tuning fork, one can correspondingly widen or narrow this range. At the same time, the time constant determining the fixed vibrations of the tuning fork also varies, which in turn affects the response speed of the regulator system of frequency deviation.

In a regulating system using the regulator described above, negative feedback may be employed as required to obtain stable regulating conditions. However, in regulating the frequency of a generator intended for use with a network analyzer, the regulator has operated normally without supplementary feedback.

To obtain the utmost accuracy in frequency stabilization and to eliminate nonlinearity, it is essential that particular attention be paid to proper design of the coils and magnetic circuit of the tuning fork. The very simple system shown in Figure 5a has coils arranged at the side of the prongs of the tuning fork. However, it has many defects, the principal ones being the presence of a constant lateral force which influences the natural frequency of the tuning fork and the non-linear dependence of oscillatory force on the magnitude of the flux. This system, therefore, cannot be employed in those cases which require great stability.

Several systems were examined that corrected these defects more or less. Some of them are shown in Figure 5 b-f. Of all the systems examined, the one shown in Figure 5d was selected because it had comparatively simple construction, together with the most essential advantages of other systems. Its action is based on the orientation of the magnetic flux from each pole along two separate core sections made of transformer sheet steel. The control coils are correspondingly divided into two separate halves one on each core section, connected in series opposition. With this arrangement, the ac component of the magnetic flux does not pass through the magnet, while the lines of force created by the constant component of the magnetic flux are directed along the prongs of the tuning fork. A tuning fork with this type of coil system, and at a frequency close to resonance (400 cps), easily generates a voltage of 15-20 v in the secondary winding, which is quite sufficient for the operation of the system.

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For accurate visual frequency control at the panel of the network analyzer, a 6E5 cathode-ray tuning indicator tube, V_7, is used in the regulator system (Figure 2). Part of the voltage of the secondary winding of transformer T1 is rectified by diode V_6 and is then applied to the grid of the 6E5. Since this voltage varies with frequency in accordance with the sharp resonance curve of the tuning fork, the 6E5 tube thereby serves as a sensitive indicator of tuning-fork resonance.

Depending on the regulated object, the output voltage of the system between points a and b can be applied: (1) directly to a supplementary excitation coil of the motor; (2) to the grid of an electron tube inserted as a shunt or as an added resistance in the excitation coil; (3) to an amplidyne; and (4) to a relay or similar apparatus employed in control devices to regulate frequency.

3. The ac source for a network analyzer is a three-phase, 16-pole generator driven by a dc motor rated at 60 kw and 3,000 rpm. To regulate its frequency, the control system shown in Figure 2 was used. The output voltage is applied to the grid of tubes V_3 and V_4, connected in parallel with excitation coil L_4 of the above-mentioned motor M. The excitation coil is supplied from an external dc source at 260v (selenium three-phase rectifier) through variable resistor R_4, which can be based to provide initial rough adjustment of excitation current.

The current flowing through ballast resistor R_4, averaging one ampere, separates into two parallel paths consisting of excitation coil L_4 and tube V_3 and V_4. A smaller part of the current, varying between zero and 300 ma, depending on grid voltage, flows through the tubes, but the larger part flows through the excitation coil. The dynamic characteristic of the two 6L6 tubes in the above circuit is around 10 ma/v. In the limits of variation of output voltage "U_{out}" between points a and be of the regulator circuit -2 to -32 v (i.e., -17±15 v), which corresponds to the previously indicated range for frequency deviation of 0.06%, the current of tubes V_3 and V_4 varies almost linearly from 300 to 20 ma. Correspondingly, the current of excitation coil L_4 changes from 150 to 200 ma, i.e., 15-20%, which is quite sufficient to maintain constant motor speed during the greatest possible variations in load, supply voltage, temperature of the motor windings, etc. For normal operation, an initial grid bias on tubes V_3 and V_4 of about -17 v is necessary, corresponding to $f = f_0$. The bias voltage is established by a small unbalance in arms R_1 and R_2 of the converter circuit.

With this method of regulation, a static frequency control is achieved without sacrificing dynamic response characteristics.

To illustrate the operation of the regulator, Figure 6 shows one of the characteristic curves during tests of the regulator under operating conditions. This curve shows how the regulator keeps the excitation current of the machine constant during arbitrary changes in the total current flowing through resistor R_4, brought about by varying R_4 while maintaining other conditions constant. The graph shows the dependence of current I_t through regulating tubes V_3 and V_4 and current Iexc in the excitation coil on total current I. (The scope of this article does not permit the presentation of design calculations for the selection of optimum circuit constants and operating conditions for the converter circuits of the regulator. However, it is intended that a separate paper will be devoted to these aspects.)

The regulator described, together with the tubes controlling the excitation current of the motor, is extremely compact [redacted] The regulator has been in operation for more than a year and has proved to be extremely reliable.

Frequency stabilization is maintained to an accuracy of hundredths of one percent. The regulator starts operating automatically when the motor starts, takes on the motor regulation promptly at 2,600 rpm, and brings it up to rated speed of 3,000 rpm smoothly, without vibration, while maintaining the frequency within the above-mentioned accuracy for load variations from zero to rated load, despite the usual fluctuations prevalent in the line voltage of the laboratory. A change in the supply voltage at the regulator itself, within wide limits, has practically no effect on its operation. The regulator starts operating at approximately 50% of rated voltage. The use of this frequency regulator in conjunction with an electronic voltage regulator having an accuracy of better than 0.1% is one of the factors which ensure accuracy and speed in carrying out calculations on the network analyzer.

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[Appended figures follow.]

[redacted]

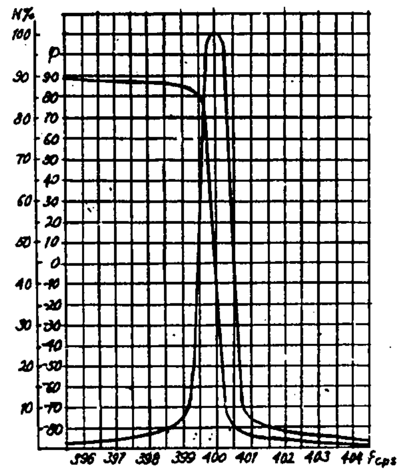

Figure 1. The Dependence of the Amptitude and Phase of Forced Vibrations of a Tuning Fork on Frequency

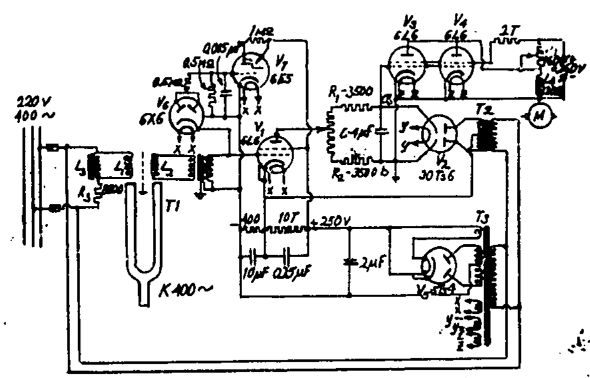

Figure 2. Circuit of Frequency Regulator

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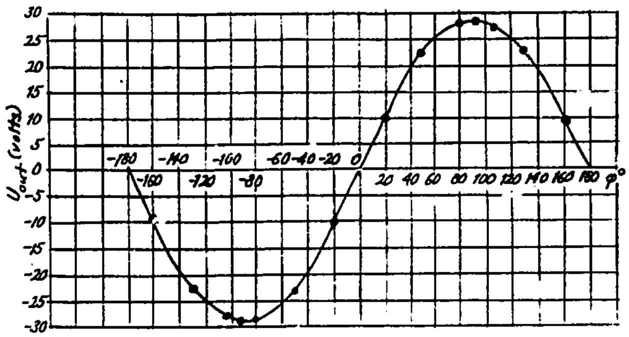

Figure 3. Relationship Between Output Voltage of the Converter-Circuit and Phase Shift

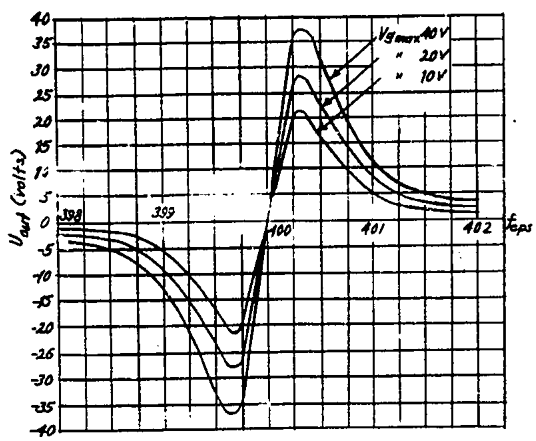

Figure 4. Dependence of Output Voltage of the Regulator Circuit on Frequency

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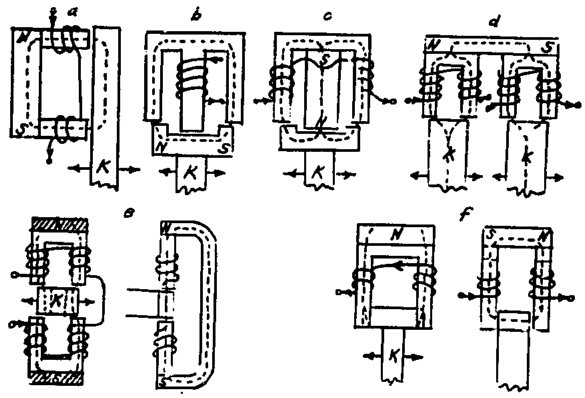

Figure 5. Variants of the Magnetic System of the Tuning Fork

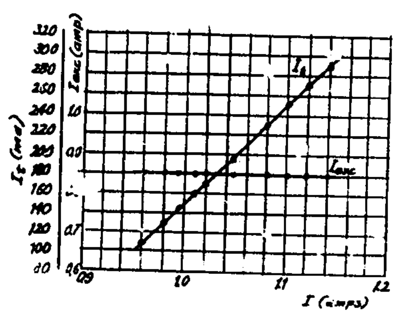

Figure 6. Dependence of Current in the Regulating Tubes and Excitati- Current on Total Current I During Regulator Operatior

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